(54) Title: CONTROLLABLE REACTOR WITH FEEDBACK CONTROL WINDING

(57) Abstract

A device for performing, individually or in combination with each other, the functions of voltage control, power factor correction, current limiting and harmonic filtering at a network, with a line voltage U_0 and a load voltage U, with the aid of a control voltage ΔU. The device comprises a controllable reactor comprising at least one control winding (7) and at least one power winding (5) for generating the control voltage ΔU, as well as a control unit (10) which, via at least one power amplifier (9), delivers a control current I_s to the control winding. The power winding is connected in series with the load (2) and through it flows a load current I_0. A measuring member (8) senses the magnetic flux (Φ) of the controllable reactor and delivers a flux voltage $V\Phi$ proportional thereto. Via measuring members, those signals which correspond to the line voltage U_0, the load voltage U, the control voltage ΔU, the load current I_0 and the flux voltage $V\Phi$ are fed back to the control unit which, in dependence thereon, via the power amplifier(s), delivers such a control current I_s to the control winding that the control voltage ΔU induced in the power winding supplements the line voltage U_0 such that the relevant functions or function are/is achieved.

Controllable reactor with feedback control winding

TECHNICAL FIELD

5   The present invention relates to a device comprising a
       controllable reactor by means of which the voltage, phase,
       current, harmonic content, etc., of an ac network may be
       influenced. The controllable reactor comprises a power winding
       and a control winding which surround the same magnetic flux.
10   The device also comprises a control and supply circuit for the
       control winding.

BACKGROUND ART, THE PROBLEM

15   During transmission of electric energy by means of alternating
       current, in a plurality of situations a need of correcting the
       voltage, the phase, the current and the harmonic content
       arises. Typical examples are:

20   Voltage control: The voltage is to be adjustable upwards or
       downwards, or the voltage is to be kept constant during
       varying loads;

       Power factor correction: The phase position between voltage
25   and current is to be changed;

       Current limiting: The current is to be limited when exceeding
       a predetermined value;

30   Harmonic filtering: Currents with a frequency different from
       the fundamental of the alternating voltage, also current
       pulses, are to be damped.

       For low voltages and currents this can be easily achieved in
35   many different ways, often with the aid of electronics.
       However, technical solutions which function satisfactorily in

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the low-voltage field can seldom be used directly for voltages
and currents which are typical of electric energy trans-
mission. The amount of energy which is released during a
control operation would lead to rapid wear of components
included in the equipment, and the locally high electric field
strength may lead to electrical breakdown of insulating
material. For example, the rotary transformer, which serves as
a simple, robust and practically stepless voltage control for
low voltage, is no alternative for voltage control of power
transformers. In that case, a voltage control is achieved with
on-load tap changers which make it possible to choose between
a number of terminals of the control winding of the trans-
former. On-load tap changers are mechanically complicated
designs and cause a large part of the transformer breakdowns.

Power factor correction require controllable inductances or
capacitances. Also here, the solutions of the low-voltage
field, for example rotary variable capacitors as controllable
capacitances, cannot be used. What is chosen is instead a
step-by-step connection or disconnection of inductances or
capacitances with the aid of circuit breakers and/or power
electronics. To be able to control with small steps, a large
number of connection units, for example circuit breakers, are
needed.

Harmonic filtering may be performed with permanently installed
filter circuits, or with stepwise connection or disconnection
of filter elements in the same way as described above for
power factor correction. Also active filtering with feedback
and use of power electronics occurs within some special fields
of use.

Current limiting is carried out either by directly breaking
the current, for example with a circuit breaker, or by placing
a device in the circuit, which functions as a variable impe-

dance, for example an inductance which may be changed by changed premagnetization of the core.

Although the control cases mentioned above have one common
5   feature, namely, to add to a given current/voltage a correcting current/voltage, solutions according to the prior art require specifically designed equipment. If only one frequency is considered, it is a question of addition of complex current and voltage values. Power factor correction and voltage con-
10   trol are two special cases of this addition.

SUMMARY OF THE INVENTION

A device according to the invention solves the problem of
15   carrying out, in a stepless manner, voltage control, power factor correction, harmonic filtering and current limiting using one and the same piece of equipment. By combining a conventional on-load tap changer with at least one device according to the invention, the problem with arcing arising in
20   the on-load tap changer can be considerably reduced and voltage levels between the positions of the on-load tap changer be chosen continuously.

A device according to the invention will normally be used in
25   connection with a network, the line voltage U_0 of which is to be supplemented with a control voltage ΔU before it reaches to a load which places high demands on the feeding voltage, referred to below as load voltage U. Normally, the load is a network comprising a number of load objects. By being able to
30   combine voltage control, power factor correction and harmonic filtering, a device according to the invention may maintain the load voltage with unchanged amplitude, phase shift between voltage and current and harmonic content even if the load contains greatly varying resistive, reactive and non-linear
35   loads. Upon exceeding a fixed maximum current to the load, the device may, in addition, limit this current.

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For each phase of the network, a device according to the
invention comprises at least one control winding and at least
one power winding with a common magnetic flux Φ which is
measured with a transducer, preferably a measuring coil
5   surrounding the same magnetic flux. The current I_0 through the
power winding and the load, referred to below as a load
current, the line voltage U_0, the load voltage U and the
voltage across the power winding which constitutes the above-
mentioned control voltage ΔU are measured with the aid of
10   suitable measuring means and are supplied to a control unit
together with a signal corresponding to the magnetic flux, for
example the voltage of the measuring coil, referred to below
as the flux voltage $V\Phi$. The control unit controls a power
amplifier which supplies the control winding with a control
15   current I_s. The relationship between the measured values I_0,
ΔU, U_0, U, $V\Phi$ and the control current is determined by the
desired function of the device.

Depending on the phase angle of the control voltage ΔU added
20   to the line voltage U_0, power may flow in both directions
between the power amplifier and the control winding. Thus, the
power source of the power amplifier must be able both to
deliver and receive power. If the voltage and/or power values
become too large to be handled by a single power amplifier,
25   the control winding may instead be sectioned with one power
amplifier for each section and a common control unit for all
the power amplifiers be used.

In its function as voltage-control equipment, the power
30   amplifier delivers a control current which gives rise to a
control voltage +/- ΔU in the power winding, depending on
whether the load voltage is to be increased or decreased. In
the case of power factor correction, a control voltage ΔU is
instead achieved which is phase-shifted by +/- $\pi/2$ in relation
35   to the line voltage U_0. A combination of power factor correc-
tion and voltage control means an arbitrary phase angle of the

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control voltage ΔU which can also be expressed as a complex
voltage which is added to the line voltage U_0.

5   In the function as a current limiter, a control current I_s is
       fed to the control winding which, for a load current I_0
       through the power winding which falls below a predetermined
       maximum value, results in the magnetic flux Φ disappearing.
       Then the control voltage ΔU across the power winding is
       reduced to the normally negligible resistive voltage drop.
10   This is equivalent to a transformer with a short-circuited
       superconducting secondary coil which becomes traversed by the
       secondary current which causes the magnetic flux to disappear.
       This method is used in the patent 94/01470-1 SE for active
       damping of magnetic fields. If the load current I_0 exceeds the
15   maximum value, the control current is no longer increased in a
       corresponding way but is maintained at a value corresponding
       to the maximum value. This means that the magnetic flux Φ
       becomes different from zero. For a load current I_0 through the
       power winding which exceeds the maximum value, a device accor-
20   ding to the invention functions as a reactor which limits this
       current by achieving an inductive voltage drop across the
       power winding. By subsequently reducing the control current I_s
       to zero, the device functions as a current-limiting reactor
       with a considerable inductance.
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       In the function as a harmonic filter, the control winding is
       fed with a control current which only contains the fundamental
       of the line voltage with a current intensity which is so
       adapted that the fundamental component of the magnetic flux
30   disappears. The load current through the power winding then
       only "sees" one, in practice negligible, resistive load for
       the fundamental, but an inductive load for all the harmonics
       and also other disturbances, for example current pulses. A
       device according to the invention is thus made to function as
35   a bandpass filter with the fundamental frequency as the centre
       frequency. The control unit may also be caused to give a con-

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trol current in opposition to current components through the
power winding which do not belong to the fundamental; the
device then functions as an active filter.

5   With a device according to the invention, it is possible to
carry out the functions individually as described above. By
Fourier series expansion of the control current I_S and super-
imposing selected frequencies on the control winding, it is
furthermore possible to simultaneously carry out the functions
10 in an optional combination with each other by controlling the
different Fourier components of the control voltage ΔU with
the Fourier components of the control current I_S. It is thus
possible, for example, to carry out voltage control as well as
power factor correction on the fundamental of the line voltage
15 U_0 while simultaneously carrying out harmonic filtering on the
other frequency components.

The invention may be regarded as an improvement of a so-called
booster transformer, where the galvanic coupling between a
20 winding of an excitation transformer and a winding of a series
transformer, which only permits voltage control, is replaced
by the control unit and the power amplifier. In this way, the
plurality of control functions already described may be
achieved.
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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a device according to the invention, connected
to a network in the form of a power transformer and a load.
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Figure 2 shows the relationship between uncorrected and
corrected voltage in a vector diagram.

Figure 3 shows a non-sinusoidal line voltage, the control
35 voltage of the device and a load voltage after filtering.

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Figures 4a and 4b show schematically combinations of an on-
load tap changer with one or more devices according to the
invention.

5   DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows a device according to the invention, which is
connected between a network in the form of a power transformer
1 and a load 2, symbolized by a resistor. The load 2 may
10   consist of a network comprising a plurality of consumers. The
power transformer has a primary winding 3 and a secondary
winding 4. The voltage of the secondary winding corresponds to
the above-mentioned line voltage U_0. In a preferred embodi-
ment, the device comprises an iron core 6 with a power winding
15   5, a control winding 7 and a measuring winding 8 for deter-
mining the magnetic flux Φ in the iron core. The power winding
is connected in series with the secondary winding and the
load, and a load current I_0 flows in the circuit. The control
winding is fed from a power amplifier 9 which is controlled
20   from a control unit 10. The power amplifier and the control
unit are fed with current from a current supply device 11,
which in turn is fed from an auxiliary winding 12 of the power
transformer 1. This has the advantage that the frequency of
the power supply corresponds to the frequency of the current
25   in the control winding, which may simplify the design of the
power amplifier. The voltage supply to the current supply
device may also take place directly from the primary or
secondary winding of the transformer.

30   Via suitable measuring means, the line voltage U_0, the load
voltage U, the load current I_0 and the voltage $V\Phi$ across the
measuring winding, which is proportional to a magnetic flux Φ
common to the power winding and the control winding, are fed
back to the control unit. Since ΔU and U fulfil the equation
35   $\Delta U = U - U_0$, also the combinations ΔU and U_0 or ΔU and U may
be supplied to the control unit instead of the combination U
and U_0, depending on which combination of measurements is

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simplest to achieve. In that case, it is also necessary for ΔU
to be measured; this is indicated in dashed lines in Figure 1.

According to the invention, the control unit is to be
5   programmed such that, on the basis of the feedback signals and
otherwise well-known relationships between these, it achieves,
via the power amplifier, the control current I_S to the control
winding which is needed for the control voltage ΔU to become
the proper supplementation of the line voltage U_0 for the
10 application in question. As described, the application may be
voltage control of the load voltage U at varying line voltage
and/or load, power factor correction, current limiting,
filtering, etc., or some combination thereof.

15 In case of voltage control with respect to amplitude, the
control voltage corresponds to the amplitude of that control
error which is obtained on a comparison between the desired
amplitude $|U|$ and the actual amplitude of the load voltage,
that is, $|\Delta U|=|U|-|U_0|$. With access to the number of winding
20 turns of the control and power windings and other data for the
magnetic circuit, the relationship between the flux Φ for a
given ΔU and the relationship between the flux Φ and the
control current I_S, respectively, may be determined. This
means that the control unit, via the power amplifier, may
25 generate that control current I_S which gives a flux propor-
tional to ΔU, in phase with or in opposition to the line
voltage U_0, in the power winding.

With access to the relationship between the line voltage U_0
30 and that control voltage ΔU with phase $+/- \pi/2$ relative to the
phase of the line voltage which is needed for a given power
factor correction of the phase of the load voltage, the ΔU
necessary for a desired power factor correction may be deter-
mined. The amplitude of the relevant load voltage is then
35 determined from the relationship $|U|^2=|U_0|^2+|\Delta U|^2$. When ΔU is
determined, the control unit can generate the required control

current via the power amplifier in the same way as described above.

A frequently occurring control case is that the load voltage U has to be controlled both in amplitude and in phase relative to a line voltage U_0. The task thus comprises, according to Figure 2, determining the ΔU, both from the amplitude and the phase point of view, which is needed for the vectorial sum of U_0 and ΔU to correspond to the desired load voltage U. If the desired load voltage U is phase-shifted by an angle φ relative to the line voltage U_0, the amplitude of ΔU is determined according to

$$|\Delta U| = \sqrt{(\ (\ |U|\cos \varphi - |U_0|\ )^2 + (\ |U|\sin \varphi\ )^2\ )}$$

and the phase shift α between ΔU and U_0 is determined from

$$\alpha = \arctan((|U|\sin \varphi)/(|U|\cos \varphi - |U_0|))$$

With ΔU determined in this way, the control unit may generate the required control voltage via the power amplifier, in the same way as described above.

When a device according to the invention is to function as a current limiter, it is a precondition that, at a load current I_0 less than an allowed maximum current I_{0max}, it shall have as small an influence on the circuit as possible. The control unit is therefore adapted such that, at a load current less than the maximum current, it generates and adapts such a control current I_s that the resultant flux from the control winding and the power winding is zero. This means that, at maximum load current I_{0max}, there is a corresponding maximum control current I_{smax}. At zero flux, the control voltage ΔU across the power winding will consist of the normally negligible resistive voltage drop caused by the relevant load current and the resistance of the power winding.

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In a preferred embodiment as a current limiter, during a
transition stage after the load current has exceeded the
maximum current, the control unit is adapted to maintain the
maximum control current I_{smax}. Because the load current

5   becomes greater than I_{0max}, during the transition stage the
flux will become different from zero which means that the
circuit will have a limited addition of inductance. By redu-
cing the control current to zero after the transition stage,
which may amount to some twenty or thirty milliseconds, the

10   device will function as a current limiting reactor with a
considerable inductance.

In an alternative embodiment as a current limiter, the
reduction of the control current may take place immediately

15   after the load current tends to exceed the maximum current,
that is, the above-mentioned transition process is excluded.

The principle of the use of a device according to the inven-
tion as an active filter is clear from Figures 3a, b and c.

20   Figure 3a shows a non-sinusoidal line voltage U_0 as a function
of time t. The control unit is arranged with a Fourier filter
which produces the sinusoidal fundamental component of the
line voltage and forms that control voltage ΔU, shown in
Figure 3b, which corresponds to the difference between the

25   relevant line voltage and its sinusoidal fundamental compo-
nent. With access to the necessary control voltage ΔU, in the
same way as above, that control current I_s may be generated
which, via the power amplifier, gives a flux in the power
winding proportional to ΔU.

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When using the device as a passive filter for the fundamental
component of a line voltage, the control voltage ΔU is to
correspond to the fundamental component and the amplitude of
the line voltage, which may both be extracted from the above-

35   mentioned Fourier filter. In the same way as above, also in
this case that control current I_s may be generated which, via

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the power amplifier, gives a flux in the power winding propor-
tional to ΔU.

Figure 4a and Figure 4b show schematically how at least one
device according to the invention may be used for stepless
voltage control together with an on-load tap changer of a
power transformer or a reactor. In Figure 4a the terminals of
an on-load tap changer are symbolized by the rings 13. The
voltage step between two terminals is δU. Two consecutive
terminals, each with a respective device according to the
invention, symbolized by the coils 14 and 15, are connected to
the point 16, where the voltage may be varied in a stepless
manner between the voltage of the two terminals by the lower
device 15 delivering a control voltage $\Delta U_1 = a\delta U$ and the upper
device a control voltage $\Delta U_2 = (a-1)\delta U$, with $0 \leq a \leq 1$. In
Figure 4b, one of the devices is replaced by a direct connec-
tion 17 which is only connected when the device 16 provides
the same control voltage ΔU as the voltage step δU between the
terminals, such that the point 16 and the upper terminal lie
on the same voltage.

Also other connections between an on-load tap changer and at
least one device according to the invention are feasible.

Connecting an on-load tap changer in this way to at least one
device according to the invention entails several advantages:

Contacts may be opened and closed in a voltage-free and hence
discharge-free manner;

The voltage of a power transformer or a reactor may be
controlled in a stepless manner;

The on-load tap changer may be designed with fewer terminals.

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A device for control of the voltage of the power transformer
need only be dimensioned for one voltage step between the
terminals.

5   In addition to the examples stated above, closely related
fields of use as well as combinations thereof may be used
within the scope of the invention. Thus, for example, a device
according to the invention may be used at the same time for
both power factor correction and filtering.

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CLAIMS

1. A device for performing, individually or in combination
with each other, the functions of voltage control, power
5   factor correction, current limiting and harmonic filtering at
a network, with line voltage U_0, for feeding a load (2), which
may comprise a plurality of consumers, with a load voltage U,
with the aid of a control voltage ΔU and wherein the device
comprises a controllable reactor comprising at least one
10   control winding (7) and at least one power winding (5) for
generating the control voltage ΔU, as well as a control unit
(10) which, via at least one power amplifier (9), delivers a
control current I_S to the control winding, and wherein the
power winding is connected in series with the load, and
15   wherein a load current I_0 flows through the power winding and
the load, and wherein a measuring member (8) is adapted to
sense the magnetic flux (Φ) of the controllable reactor and to
deliver a flux voltage $V\Phi$ proportional to the magnetic flux,
characterized in that, via measuring members, those signals
20   which correspond to the line voltage U_0, the load voltage U,
the control voltage ΔU, the load current I_0 and the flux
voltage $V\Phi$ are fed back to the control unit which is
programmed such that, on the basis of the feedback signals, it
delivers via the power amplifier(s) such a control current I_S
25   to the control winding that the control voltage ΔU induced in
the power winding supplements the line voltage U_0 such that
the relevant functions or function are/is achieved.

2. A device for voltage control according to claim 1,
30   characterized in that a control error arisen during voltage
control constitutes a control voltage ΔU and that the control
unit (10), via the power amplifier (9), is adapted to generate
a control current I_S which provides a magnetic flux Φ,
proportional to ΔU, in phase with or in opposition to the line
35   voltage U_0, such that $U_0 + \Delta U = U$ corresponds to the desired
load voltage U.

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3. A device for power factor correction according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which corresponds to a magnetic flux Φ, which results in a

5   control voltage ΔU which is phase-shifted relative to U_0 by $+/- \pi/2$, such that the voltage amplitudes, symbolized by $| \ |$, fulfil the equation $|U_0|^2 + |\Delta U|^2 = |U|^2$ where U is the desired load voltage.

10   4. A device for voltage control and power factor correction according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which corresponds to a magnetic flux Φ, which results in a control voltage ΔU which has such a phase

15   and amplitude that the load voltage U is given a desired amplitude $|U|$ and a desired phase shift φ towards the line voltage U_0.

     5. A device for current limiting according to claim 1,
20   **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S to the control winding which, for a load current I_0 through the power winding which falls below a given maximum value I_{0max}, results in the magnetic flux Φ disappearing but which for a

25   load current I_0 which exceeds the given maximum value does not exceed the corresponding maximum value I_{smax} of the control current and where the same control current I_S within a few tens of milliseconds drops to zero.

30   6. A device for current limiting according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S to the control winding which, for a load current I_0 through the power winding which falls below a given maximum value, results

35   in the magnetic flux Φ disappearing but where the same control

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current I_S for a load current I_0 which exceeds the given maximum value is immediately reduced to zero.

7. A device for passive harmonic filtering according to claim
5 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which only contains the sinusoidal fundamental component of the line voltage and that the amplitude of the control current is such that the fundamental component of the magnetic flux
10 disappears.

8. A device for active harmonic filtering according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current
15 I_S which only contains the sinusoidal fundamental component of the line voltage, that the amplitude of the control current is so great that the fundamental component of the magnetic flux disappears and that the control current, in addition, contains the harmonics of the load current I_0 in opposition.
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9. A device according to any of claims 1 to 8, **characterized** in that the control winding is sectioned into part-windings.

10. A device according to claim 9, **characterized** in that a
25 power amplifier (9) is arranged for each part-winding of the control winding.

11. A device according to any of claims 1 to 4, **characterized** in that it is arranged together with at least one on-load tap
30 changer of a power transformer or a reactor for voltage control between the terminals (13) of the on-load tap changer.

12. A device according to any of claims 1 to 11, **characterized** in that the device is arranged adjacent to a
35 power transformer (1).

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13. A device according to claims 12, **characterizod** in that the power supply to the power amplifier (9) takes place with at least one auxiliary winding (12) of the power transformer (1).

14. A device according to claims 12, **characterized** in that the power supply to the power amplifier (9) takes place from the primary or secondary winding of the power transformer.

15. A device according to any of claims 1 to 14, **characterizod** in that the control winding and the power winding are wound on a common core (6) of magnetizable material.
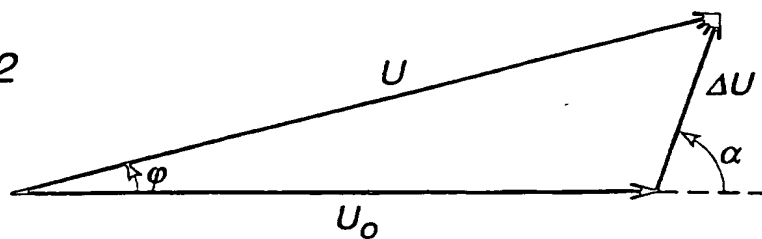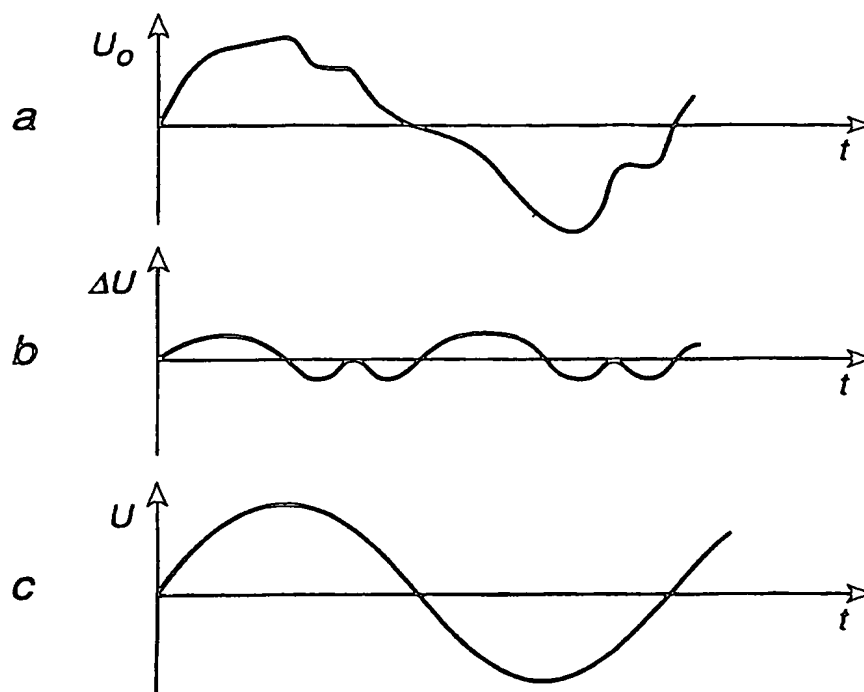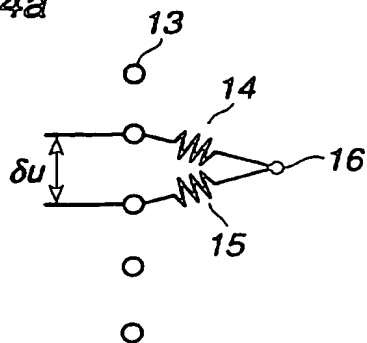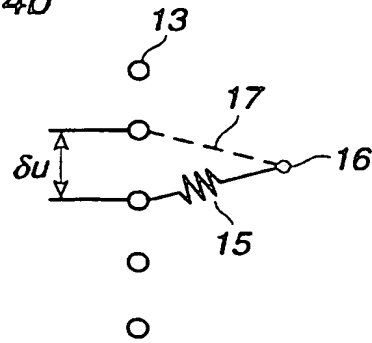
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Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

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INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G05F 1/32, H02J 3/01, H02J 3/12, H02H 9/02
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G05F, H02J, H02H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 1513876 A (HONEYWELL INC.), 18 Sept 1969 (18.09.69), page 1, line 1 - page 2, line 7	1
A	Patent Abstracts of Japan, Vol 13,No 444, E-828, abstract of JP,A,1-170328 (NISSIN ELECTRIC CO LTD), 5 July 1989 (05.07.89)	1
A	US 4833585 A (S. MORAN), 23 May 1989 (23.05.89), column 1, line 44 - column 2, line 2	1
A	US 5341281 A (G. SKIBINSKI), 23 August 1994 (23.08.94), abstract	1

[X] Further documents are listed in the continuation of Box C.   [X] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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Date of the actual completion of the international search	Date of mailing of the international search report
17 June 1997	28.06.97
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Håkan Sandh Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SE 97/00424

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3628057 A (HANS MUELLER), 14 December 1971 (14.12.71), column 1, line 35 - line 75 --	1
A	WO 8701834 A1 (HASLER AG), 26 March 1987 (26.03.87), abstract --	1
A	WO 9503645 A1 (SIEMENS SKTIENGESELLSCHAFT), 2 February 1995 (02.02.95), page 2, line 4 - page 3, line 34 -- --------	1

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 1513876 A	18/09/69	US 3398354 A	00/00/00
US 4833585 A	23/05/89	JP 2087933 A	28/03/90
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